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Estimating Evaporation and Evapotranspiration From Climatic Data

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INTRODUCTION

The planning and design of irrigation systems requires, at the outset, an estimate of water requirements. This has long been recognized and some of the earliest work of the U. S. Department of Agriculture and the state experiment stations was the determination of the amount of water consumed by agricultural crops. Since the beginning of the century, a large amount of work has been done on soil-water-plant relations, and the determination of evapotranspiration from agricultural crops and phreatophytes. A number of very useful concepts have been developed during this period.

The objective of much of the research work, especially in the early days, was to obtain practical answers to the problem of how much irrigation water was needed for the specific crops grown in the area. Relatively little was done to relate the actual evapotranspiration to the climatic conditions so that knowledge gained in one area could be transferred reliably from one climatic zone to another.

Blaney and Criddle (1945) developed and published a formula for estimating consumptive use for agricultural crops. Since that time this formula has been extensively used throughout the world for estimating water requirements. When the writer was in the Mediterranean countries in 1958, he found that every engineering firm, whose reports he examined, was using the Blaney-Criddle formula for estimating water requirements.

At that time, most published data on the coefficients for this formula were on annual values of K rather than monthly values, k. His feeling was that the values of K used, based on determinations in western United States, were too low for the hot dry areas to which they were applied. This created a renewed interest in the problem of evapotranspiration and a desire to see if a more reliable formula for estimating evaporation and evapotranspiration could be developed. The first research project engaged in after returning to Logan was a study of water requirements of waterfowl marshlands, and this provided an opportunity to work on this problem.

Brief Review of Literature

Interest in evaporation and evapotranspiration is not of recent origin. One of the earlier writers on the subject was Dalton (1798) who showed that the rate of evaporation was proportional to the difference between the water vapor pressure at the evaporating surface and in the atmosphere. The Dalton principle, that the evaporation is a function of the vapor pressure deficit, is the basis of all vapor transfer formulas that have been developed since that time.

According to Abbe (1905), the effect of sunshine and heat in stimulating transpiration was studied in England as early as 1691. It was not until the early part of the twentieth century that the terms "consumptive use" and "evapotranspiration" came into general use.

where

R_s = the solar and sky radiation, short wave

R_{et} = the effective or net thermal radiation

r = the reflectance or albedo

A = heat flux to the air, and

G = heat flux to the ground

From the data, they plotted the ratio, Et/R_s as a function of the growing season for different crops and obtained curves somewhat similar to Hansen's (1963) unique consumptive use curve. Relating the ratio, Et/R_s, to the temperature, they obtained

$$Et/R_s = 0.014\,T - 0.37 \qquad (13)$$

For areas where incident radiation values are not available, they gave two equations

$$R_s = R_{so}\,(0.35 + 0.61\,S) \qquad (14)$$

attributed to Fritz and MacDonald (1949) and

$$R_s = R_{so}\,[1 - 0.1\,n\,(1-k)] \qquad (15)$$

from Budyko (1958).

In these equations,

R_{so} = solar radiation on cloudless days

S = possible sunshine percentage, expressed decimally

k = a mean annual coefficient, varying with latitude from 0.35 at the equator, to 0.32 for latitudes of 25 to 35° north, then increasing to 0.40 for latitude 60°

n = cloud cover in tenths (scale 0 to 10)

Many others have proposed formulas for evaporation or evapotranspiration, or have suggested modifications of commonly used formulas, such as Phelan's modification of the Blaney-Criddle formula as given by Quackenbush and Phelan (1965) where $k_c\, k_t$ is substituted for the k in the Blaney-Criddle formula. The coefficient, k_c, is a crop coefficient, values for each month being determined experimentally, and

$$k_t = 0.173\, t - 0.314 \qquad (16)$$

<u>Studies at Utah State University</u>

The purpose of this paper is to discuss the formulas that have been developed at Utah State University by graduate students working under my direction. The objectives of these studies have been to develop formulas that

1. Take into consideration more of the climatic parameters that affect evaporation and evapotranspiration.

2. Use climatic data of the type published in the Weather Bureau's State Climatological Data.

3. Are easy to apply.

The approach was both rational and empirical. The basic formula can be written

$$E = K R C \quad . . . . (17)$$

in which

E = the evaporation or evapotranspiration

K = a constant, determined from an analysis of many data

R = the theoretical solar radiation reaching the earth's outer atmosphere, expressed in the same units as E

C = an empirical coefficient, which is the product of any number of subcoefficients each expressing the affect of a given climatic or other factor

Thus,

$$C = C_T \, C_H \, C_W \, C_S \, C_E \text{ etc.} \quad . . . . (18)$$

where T, H, W, S, and E are temperature, humidity, wind, sunshine, and elevation, etc. The coefficients for these climatic factors were developed from an analysis of the data. In theory, each coefficient represents the affect of a single factor considering all other factors constant.

Each coefficient has generally been expressed as a second degree equation of the form

$$C_x = A + B X + C X^2 \quad . . . . (19)$$

except where the data suggested a different form of equation.

For a standard value of the factor, which was approximately a mean value, each coefficient was made unity. For example,

$$C_T = 1.0 \qquad \text{when} \qquad T = 68^{o}F\ (20^{o}C)$$

This determined the average value of the constant K.

The procedure suggested here may appear very complex and time consuming; however, the opposite is actually the case. Once determined, each coefficient can be plotted as a function of the climatic factor, or better, tabulated for a full range of values, with both the coefficient and the logarithm of the coefficient given. Values of R are also tabulated for each month as a function of latitude.

In order to compute the evaporation for a given month, mean values of each factor are tabulated. From the graphs, or tables, values of the coefficients, or logarithms of the coefficients are next determined. The computation is then simply a matter of multiplying coefficients or adding logarithms, and taking the antilogs.

When data on one or more of the climatic factors are missing, the user has two choices:

1. Omit the coefficient by considering it unity.
2. Estimate the probable value of the missing factor, if it is believed appreciably different from the standard value.

Formulas that contain only one, two, or three climatic factors, must, of course, consider other factors to be of a normal value, or the value of the constant or coefficient must be estimated to take this into consideration. For example, in the application of the Blaney-Criddle formula, one must

1. Consider that humidity, sunshine, wind, etc. have no effect, or
2. Consider that they are all of normal values, or
3. Adjust the value of the coefficient, k, to take these factors into consideration.

Those who have had occasion to compute the values of k from actual data realize that k varies greatly, and that anyone using this formula must exercise good judgment in the selection of k values to obtain reliable values of E (evaporation or evapotranspiration).

Pan Evaporation in Northern Utah

The first attempt at developing a formula was for pan evaporation for Northern Utah. There were five evaporation stations in the area from Logan on the north to Provo on the south, a distance of 110 miles, all along the Wasatch front, east of the Great Salt Lake. The available data for these stations were tabulated. Records ranged from 37 years at Utah Lake, to only four years at the Saltair Salt Plant. The analytical procedure used for these first studies, and with modifications in later studies, has been discussed by Christiansen (1960), Christiansen and Patil (1961), Patil (1962), Mathison (1963), Grassi (1964), Al-Barrak (1964), Palayasoot (1965), Mehta (1965), and Christiansen and Mehta (1965). The initial procedure, described here only very briefly, consisted of tabulating the monthly pan evaporation, the theoretical radiation for the month (in equivalent inches of evaporation), the mean temperature, and the wind velocity at the station, and the relative humidity, and sunshine percentage at the Salt Lake Airport, the nearest station for which these data were available. The first step was to divide the evaporation by the radiation and make this ratio a function of temperature, T. Thus,

$$Ev/R = f\ T \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (20)$$

In this first analysis, the function was assumed to be linear, and the best fit equation was

$$Ev/R = 0.00744\ T - 0.0439$$

$$= k_t\ C_T$$

For $T = 68^{o}F$, $C_T = 1.0$, then $k_t = 0.462$

and

$$C_T = 0.0161\ T - 0.095 \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (21)$$

The second step was to make the ratio

$$Ev/(R\ k_t\ C_T) = f\ W$$

$$= k_w\ C_W$$

For each step, the constants, k, were combined so that the final value of K was

$$K = k_t\ k_w\ k_s\ k_h \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (22)$$

Because of heat storage effects, and possibly other factors, it was found that a monthly coefficient was also necessary to obtain the best results.

The final equation was

$$Ev = K R C_T C_W C_S C_H C_M \quad . . . . \quad (23)$$

where

$$K = 0.470 \quad . . . . \quad (24)$$

$$C_T = 0.016 T - 0.095 \quad . . . . \quad (25)$$

$$C_W = 0.140 W + 0.650 \quad (W = \text{miles/hour at pan}) \quad . . . \quad (26)$$

$$C_S = 0.575 S + 0.560 \quad . . . . \quad (27)$$

$$C_H = 1.106 - 0.340 H \quad . . . . \quad (28)$$

(H = the average monthly relative humidity at 11 a.m. and 5 p.m. as published in Climatological Data for Utah.)

C_M values were tabulated. For the months April through October, they were, respectively: 0.933, 0.943, 0.962, 0.991, 1.063, 1.081, and 1.044 with a mean value of 1.00.

In the second analysis of data by Christiansen and Patil (1961), the study was broadened to include 54 stations in the western states and Texas ranging in latitude from 26.15 to 48.50 north, and in elevation from 9 to 6007 feet above sea level. Coefficients for latitude, C_L, and for elevation, C_E, were determined. The other coefficients obtained in this analysis were not greatly different from those previously obtained from the Utah data.

The results of these analyses were sufficiently encouraging to interest Patil (1962) in choosing this subject as an M. S. Thesis study. He tabulated

3232 months of records for 40 stations in the Western States and Texas, which included 10 years of records for most stations. He fitted second degree equations to the data, using the IBM 1620 computer in the analysis. He found the following coefficients:

$$K = 0.530 \quad \ldots \quad (29)$$

$$C_T = -1.203 + 0.0463\,T - 0.000204\,T^2 \quad (T \text{ in } {}^{o}F) \quad \ldots \quad (30)$$

$$C_W = 0.786 + 0.00385\,W - 0.0000047\,W^2 \quad (W \text{ in miles/day}) \quad (31)$$

$$C_S = 0.458 + 0.00568\,S - 0.0000136\,S^2 \quad (S \text{ in } \%) \quad \ldots \quad (32)$$

$$C_H = 1.141 - 0.00336\,H - 0.0000045\,H^2 \quad (H \text{ in } \%) \quad \ldots \quad (33)$$

$$C_E = 0.936 + 0.00350\,E - 0.0000156\,E^2 \quad (E \text{ in units, 100 ft.}) \quad (34)$$

$$C_M = 1.000 + 0.098 \cos(30\,N - 20) \quad (N = \text{month, Jan.} = 1.0) \quad (35)$$

He tabulated values of all coefficients and their logarithms.

Mathison (1963), a graduate student from Venezuela, reasoned that Patil's monthly coefficients would not apply to the tropics, and because relative humidity was often not available, he suggested that the difference between the mean monthly maximum and minimum temperatures might be used as an index of humidity. Using the same data as Patil, but different analytical procedures, he developed an independent set of coefficients. Instead of beginning with

$Ev/R = f\,T$, he chose to first express

$Ev = f\,R$, so that his final formula was

$$Ev = C_R\,C_T\,C_W\,C_{\Delta T}\,C_S\,C_E\,C_{\cos(L-D)}\,C_M \quad \ldots \quad (36)$$

where

$$C_R = 0.20\,R + 0.015\,R^2 \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \tag{37}$$

$$C_T = -0.26 + 0.0242\,T - 0.000075\,T^2 \quad . \; . \; . \; . \; . \; . \; . \tag{38}$$

$$C_W = 0.80 + 0.0035\,W - 0.0000027\,W^2. \quad . \; . \; . \; . \; . \; . \tag{39}$$

$$C_{\Delta T} = 0.45 + 9.6 \times 10^{-4}\,\Delta T^2 - 2.76 \times 10^{-7}\,\Delta T^4 \quad . \; . \; . \tag{40}$$

$$C_{(L-D)} = 1.16 + 0.42 \cos (L-D) - 0.7\,[\cos (L-D)]^2 \quad . \; . \tag{41}$$

where L = latitude, $^{\circ}$N; D = mean declination of sun for month

$$C_E = 0.967 + 0.0035\,E - 0.0000156\,E^2 \quad . \; . \; . \; . \; . \; . \tag{42}$$

with E in units of 100 feet

$$C_M = 1.00 + 0.00155\,(L-D) \cos [\pi/6\,(N + 1)] \quad . \; . \; . \; . \tag{43}$$

where N = month, January = 1.0

In order to simplify application of his formula, he combined the coefficients which were all functions of the month, latitude, and declination, thus:

$$C_C = C_R\,C_{(L-D)}\,C_M \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \tag{44}$$

and tabulated all values with their logarithms.

In order to see how well these formulas, and others, agreed with actual data when applied to climatic conditions quite different from those for which the formulas were developed, Patel and Christiansen (1963) selected fourteen stations, with 374 months of record from Iowa, Indiana, Georgia, Puerto Rico, Panama Canal Zone, Hawaii, and Alaska, and compared the evaporation with the results from the formulas.

In addition to Patil's and Mathison's formulas, comparisons were made with a multiple regression equation, developed from Patil's data, and with the formulas of Hargreaves and Blaney-Criddle.

Comparisons with the Blaney-Criddle formula were somewhat difficult because it was first necessary to decide on proper values of k for the locations chosen. For this purpose, the data for the fourteen stations were divided into three groups, which were assumed to represent different climatic zones. Group 1 included Iowa, Indiana, and Georgia; group 2, Puerto Rico, Panama Canal Zone, and Hawaii; and group 3, Alaska. Mean values of k for each month for each group were computed, and these values were plotted against the month. These computed k values were then adjusted by drawing a smooth curve through the points. Values of Ev from the Blaney-Criddle formula were then computed and compared with the actual evaporation by computing the mean of the absolute errors.

The adjusted values of k used in this comparison are given in Table 1. All comparisons were then made by averaging the absolute values of the difference between the actual and computed values for all formulas. Mean values of the actual evaporation, the computed evaporation from each formula, and the mean of the absolute differences were computed for each station. The mean values of the absolute differences for each formula expressed as a percentage, are given in Table 2.

Table 1. Adjusted values of k used for comparing the Blaney-Criddle formula with evaporation records.

Month	Group 1	Group 2	Alaska
January	----	0.91	----
February	----	0.94	----
March	1.01	0.96	----
April	1.03	0.97	----
May	1.03	0.97	0.76
June	1.02	0.95	0.69
July	1.00	0.93	0.60
August	0.95	0.90	0.49
September	0.90	0.86	0.40
October	0.84	0.83	----
November	0.80	0.81	----
December	----	0.85	----

Group 1--Iowa, Indiana, and Georgia
Group 2--Puerto Rico, Panama Canal Zone, and Hawaii

Table 2. Mean values of absolute differences in actual and computed evaporation. From Patel and Christiansen (1963)

Formula	Mean Computed Ev	Difference in Mean	Mean Abs. Dif.
	inches	%	%
Mean value of Ev	5.64	----	----
Patil	6.38	+13.1	16.3
Mathison	5.51	- 2.3	16.4
Multiple regression	5.05	-11.5	54.8
Hargreaves	5.01	-11.2	22.5
Blaney-Criddle	5.70	+ 1.1	16.8

In this comparison, the results for the Blaney-Criddle formula cannot be compared directly with the others. Had any constant value of k, or any assumed values of k for each month, been used in the computations without first calculating mean values from the data, the mean difference would undoubtedly have been much higher. Even using the mean adjusted values for the three groups the mean of the absolute differences was slightly higher than for the Patil and Mathison formulas. The multiple regression equation proved to be worthless when applied to different climatic conditions. The Patil formula gave results that were generally high, and the Hargreaves formula gave results that were generally low. The Mathison and Blaney-Criddle formulas gave results that were both high and low.

The next study by Grassi (1964) was the first attempt to develop a formula for evapotranspiration, the original purpose of the studies. For these analyses, evapotranspiration data were obtained from Jensen and Haise (1963). Grassi tabulated the data and calculated values of R for each period for which the data were obtained, which varied from less than 1 week to more than 2 weeks. Results were expressed in inches per day. He varied the basic procedure used in the previous analysis in an attempt to obtain coefficients that were more independent of other factors where a correlation existed.

Briefly, the procedure was to first consider only the data for field crops for which the cloud cover, Clc, difference between maximum and mean temperature, Td, and wind velocity, W, were within a standard deviation of the mean values, and for which the crop cover was in excess of 70 percent. This reduced the data to 166 cards. Using these data, coefficients for radiation, C_R, and temperature, C_T, were developed by first computing C_R, then Clc, and C_T. The procedure was repeated computing C_T as a function of Et and Clc. A new equation for C_T was then determined using the mean of the first and second determinations. From this value of C_T, a new value of C_R was determined, and again repeating the process, a new value of C_T was determined.

The additional cards for temperature difference, outside the standard deviation range, were added but it was found that a coefficient for temperature difference, as a humidity index, was not significant.

Next the cards for wind outside the standard deviation range were added and again it was found that there was no significant correlation. The cards for crop cover below 70 percent were then added and a crop cover coefficient, C_{Crc}, was determined. Using the same data, a coefficient for vegetative cycle, C_{Vc}, was determined in lieu of the crop cover coefficient. The cards for alfalfa, except for periods immediately after irrigation, for which the crop cover might not be considered 100 percent, were then added and a new coefficient for temperature was developed from the much larger number of cards. An analysis was made for elevation, but no significant relation was found.

Using similar procedures, he developed a second formula for Et as a function of the incident radiation, Rs, and climatic factors. A third formula for Et, as a function of pan evaporation, Ev, and climatic factors, was also developed.

The last step was to compute mean values of a crop factor, F, for each crop for each of the formulas.

The first formula for alfalfa and field crops, as developed by Grassi can be written

$$Et = 0.215 \; C_R \, C_{Clc} \, C_T \, C_{Td} \, C_{Crc} \, F \quad \text{(in./day)} \quad . \; . \; . \; . \quad (45)$$

in which

$$C_R = 0.18 + 1.46 \; R \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (46)$$

$$C_{Clc} = 1.15 - 0.05 \; Clc \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (47)$$

$$C_T = 0.036 + 0.0219 \; T - 0.0001136 \; T^2 \quad . \; . \; . \; . \; . \; . \quad (48)$$

$$C_{Td} = 0.936 + 0.00426 \; Td \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (49)$$

$$C_{Crc} = 0.111 + 0.0141 \; Crc - 0.0000521 \; Crc^2 \quad . \; . \; . \; . \; . \quad (50)$$

F = crop factor, for which he found

Alfalfa = 1.09	Oats = 0.89
Beans = 0.98	Potatoes = 1.02
Corn & Sugar Beets = 1.00	Sorghum = 1.16
Cotton = 1.08	Winter Wheat = 1.10

In lieu of crop cover, the formula can be used with a vegetative cycle percentage, Vc, for which the coefficient is

$$C_{Vc} = 0.100 + 0.028 \; Vc - 0.000249 \; Vc^2 \quad . \; . \; . \; . \; . \; . \; . \quad (51)$$

Grassi also developed formulas expressing the evapotranspiration as a function of the measured incident radiation, Rs, and climatic factors; and as a function of the pan evaporation, Ev, and climatic factors.

The last study was by Mehta (1965) which has been reported by Christiansen and Mehta (1965). In this study, most of the data used by Patil, Mathison, and Patel were used and in addition new data were added from Nigeria, Canada, and Peru. Some of the techniques developed by Grassi, to make the coefficients more independent of each other, were incorporated in these studies.

The final formula and the coefficients used are:

$$Ev = 0.468\, R\, C_T\, C_W\, C_H\, C_S\, C_E\, C_M \quad \ldots\ldots \quad (52)$$

where

R = extra-terrestrial radiation in evaporation units, same as Ev.

$$C_T = 0.1532 + 0.0074\, T + 0.0000546\, T^2 \quad \ldots\ldots \quad (53)$$

where T is mean monthly temperature, $^{\circ}F$.
$C_T = 1.0$ for $T = 68^{\circ}F$, or $20^{\circ}C$

$$C_W = 0.79 + 0.0037\, W - 0.00000333\, W^2 \quad \ldots\ldots \quad (54)$$

where W is mean wind velocity at evaporation pan in miles per day. $C_W = 1.0$ for $W = 60$ miles/day, or 96.56 km/day

$$C_H = 1.202 - 0.00353\, H - 0.0000381\, H^2 \quad \ldots\ldots \quad (55)$$

where H is mean daytime relative humidity, or mean relative humidity at noon, percent. $C_H = 1.0$ for $H = 40$ percent

$$C_S = 0.402 + 0.019\, S - 0.00028\, S^2 + 0.0000017\, S^3 \quad \ldots \quad (56)$$

where S is percent of possible sunshine. $C_S = 1.0$ for $S = 80$ percent

$$C_E = 0.9654 + 0.0362\,E - 0.0016\,E^2 \quad . \quad . \quad . \quad . \quad . \quad . \qquad (57)$$

where E is the elevation in units of 1000 feet. $C_E = 1.0$ for $E = 1.$ (1000 feet)

C_M = monthly coefficient. Values were tabulated for 16 climatic regions.

In order to make this formula readily usable, Tables were prepared for all coefficients giving the climatic factor, the coefficient, and the logarithm of the coefficient. For C_T, C_W, and C_E, values of the factor were also given in metric units.

The formula can be applied where some of the climatic data are missing because all coefficients are equal to 1.0 for an approximate average value of the climatic factor. In the application, the value of a missing factor can either be estimated, or the coefficient omitted, which assumes the value to be 1.0.

Tables for Christiansen-Mehta Formula

To simplify the use of the formula, Tables 3 to 10 are included in the Appendix. Table 4 gives the extra-terrestrial radiation, expressed as evaporation in inches per month for latitudes from 50 S to 60 N. Table 5 gives values of the temperature coefficient, C_T, with logarithms. Table 6 gives values of the humidity coefficient, C_H, with logarithms. Table 7 is the sunshine coefficient, C_S, and Table 8 is for the elevation coefficient, both with logarithms.

The use of the equations or tables, without a monthly coefficient, should make it possible to estimate pan evaporation from climatological data within 20 percent of mean monthly values for most locations in the world. By using monthly coefficients, based on mean values for various regions, as given in Tables 9 and 10, somewhat closer estimates should be possible. Tables 3 to 10 are from Christiansen-Mehta (1965).

Summary and Conclusions

From the formulas and tables presented here, evaporation as measured with a standard class A evaporation pan can be estimated with reasonable accuracy from extra-terrestrial radiation and climatic data. Pan evaporation data are useful in estimating evaporation losses from reservoirs and lakes, and for estimating evapotranspiration from agricultural crops using procedures such as Hargreaves', Pruitt's, or Grassi's relating evapotranspiration to pan evaporation.

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APPENDIX

Table 3. Solar radiation, R, at top of atmosphere. Expressed as equivalent evaporation at 20° C.*

Latitude	Jan.	Feb.**	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
North						Inches						
60	1.76	3.93	8.53	13.28	18.05	19.51	19.12	15.39	10.23	5.68	2.27	1.19
50	4.59	6.65	11.27	15.12	19.01	19.80	19.72	16.91	12.48	8.70	5.15	3.80
45	6.05	7.99	12.53	15.89	19.34	19.88	19.90	17.52	13.51	10.12	6.60	5.21
40	7.53	9.29	13.69	16.56	19.57	19.89	20.00	18.02	14.45	10.44	8.03	6.67
35	9.03	10.54	14.74	17.12	19.69	19.80	20.00	18.41	15.29	12.66	9.45	8.16
30	10.52	11.72	15.68	17.57	19.70	19.60	19.90	18.68	16.02	13.78	10.80	9.66
25	11.97	12.82	16.50	17.90	19.59	19.28	19.68	18.82	16.63	14.80	12.10	11.15
20	13.35	13.83	17.20	18.10	19.35	18.84	19.34	18.83	17.11	15.74	13.34	12.61
15	14.63	14.74	17.77	18.16	18.98	18.29	18.87	18.70	17.45	16.60	14.50	14.03
10	15.81	15.54	18.20	18.07	18.48	17.63	18.27	18.44	17.65	17.36	15.57	15.36
5	16.88	16.22	18.49	17.85	17.86	16.86	17.55	18.05	17.72	17.98	16.53	16.59
Equator	17.84	16.78	18.63	17.50	17.12	15.99	16.71	17.53	17.67	18.42	17.37	17.70
South												
5	18.68	17.23	18.62	17.03	16.27	15.02	15.77	16.88	17.46	18.68	18.09	18.67
10	19.40	17.58	18.47	16.43	15.32	13.95	14.73	16.10	17.15	18.80	18.70	19.51
15	20.02	17.72	18.19	15.71	14.27	12.79	13.60	15.20	16.70	18.80	19.19	20.23
20	20.52	17.84	17.79	14.87	13.12	11.57	12.39	14.20	16.12	18.70	19.55	20.73
25	20.90	17.84	17.27	13.92	11.89	10.29	11.11	13.17	15.42	18.50	19.77	21.21
30	21.14	17.70	16.63	12.86	10.58	8.95	9.77	12.00	14.61	18.18	19.85	21.56
35	21.28	17.42	15.84	11.70	9.21	7.57	8.38	10.77	13.70	17.72	19.81	21.78
40	21.22	17.00	14.92	10.56	7.80	6.19	6.96	9.49	12.69	17.11	19.66	21.86
50	20.88	15.76	12.68	8.00	5.09	3.59	4.16	6.28	10.31	15.44	19.07	21.65

*Computed from data by Napier Shaw (1942).

**February computed for average of 28.25 days.

Table 4. Temperature, coefficient of temperature and log C_T.

T	T	C_T	Log C_T	T	T	C_T	Log C_T	T	T	C_T	Log C_T
°F	°C	----	----	°F	°C	----	----	°F	°C	----	----
35	1.67	.526	-.2790	60	15.56	.874	-.0584	85	29.44	1.291	.1107
36	2.22	.539	-.2687	61	16.11	.890	-.0508	86	30.00	1.309	.1168
37	2.78	.551	-.2585	62	16.67	.905	-.0433	87	30.56	1.327	.1228
38	3.33	.564	-.2485	63	17.22	.921	-.0359	88	31.11	1.345	.1287
39	3.89	.577	-.2387	64	17.78	.936	-.0286	89	31.67	1.364	.1346
40	4.44	.590	-.2290	65	18.33	.952	-.0213	90	32.22	1.382	.1405
41	5.00	.603	-.2194	66	18.89	.968	-.0141	91	32.78	1.401	.1463
42	5.56	.617	-.2099	67	19.44	.984	-.0070	92	33.33	1.419	.1520
43	6.11	.630	-.2006	68	20.00	1.000	.0000	93	33.89	1.438	.1578
44	6.67	.643	-.1914	69	20.56	1.016	.0070	94	34.44	1.457	.1635
45	7.22	.657	-.1824	70	21.11	1.033	.0138	95	35.00	1.476	.1691
46	7.78	.671	-.1734	71	21.67	1.049	.0207	96	35.56	1.495	.1747
47	8.33	.685	-.1645	72	22.22	1.066	.0275	97	36.11	1.515	.1803
48	8.89	.699	-.1558	73	22.78	1.082	.0343	98	36.67	1.534	.1858
49	9.44	.713	-.1471	74	23.33	1.099	.0409	99	37.22	1.554	.1913
50	10.00	.727	-.1386	75	23.89	1.116	.0475	100	37.78	1.573	.1967
51	10.56	.741	-.1302	76	24.44	1.133	.0541	101	38.33	1.593	.2022
52	11.11	.755	-.1218	77	25.00	1.150	.0606	102	38.89	1.613	.2075
53	11.67	.770	-.1136	78	25.56	1.167	.0671	103	39.44	1.633	.2128
54	12.22	.784	-.1054	79	26.11	1.184	.0735	104	40.00	1.653	.2181
55	12.78	.799	-.0974	80	26.67	1.202	.0798	105	40.56	1.673	.2234
56	13.33	.814	-.0894	81	27.22	1.219	.0861	106	41.11	1.693	.2286
57	13.89	.829	-.0815	82	27.78	1.237	.0923	107	41.67	1.713	.2338
58	14.44	.844	-.0737	83	28.33	1.255	.0985	108	42.22	1.734	.2390
59	15.00	.859	-.0660	84	28.89	1.273	.1047	109	42.78	1.755	.2441

$$C_T = 0.1532 + 0.0074\ T + 0.0000546\ T^2$$

Table 5. Wind, coefficient of wind, and log C_W.

W	W	C_W	Log C_W	W	W	C_W	Log C_W
mi/day	km/day	----	----	mi/day	km/day	----	----
0	0.00	.790	-.1023				
5	8.05	.808	-.0923	155	249.45	1.283	.1083
10	16.09	.827	-.0826	160	257.50	1.297	.1128
15	24.14	.845	-.0732	165	265.54	1.310	.1172
20	32.19	.863	-.0641	170	273.59	1.323	.1214
25	40.23	.880	-.0553	175	281.64	1.336	.1256
30	48.28	.898	-.0467	180	289.68	1.348	.1297
35	56.33	.915	-.0383	185	297.73	1.361	.1337
40	64.37	.933	-.0302	190	305.78	1.373	.1375
45	72.42	.950	-.0223	195	313.82	1.385	.1414
50	80.47	.967	-.0147	200	321.87	1.397	.1451
55	88.51	.983	-.0072	205	329.92	1.409	.1487
60	96.56	1.000	.0000	210	337.96	1.420	.1523
65	104.61	1.016	.0070	215	346.01	1.432	.1558
70	112.65	1.033	.0139	220	354.06	1.443	.1592
75	120.70	1.049	.0206	225	362.10	1.454	.1625
80	128.75	1.065	.0272	230	370.15	1.465	.1657
85	136.79	1.080	.0336	235	378.20	1.476	.1689
90	144.84	1.096	.0398	240	386.24	1.486	.1603
95	152.89	1.111	.0459	245	394.29	1.497	.1751
100	160.94	1.127	.0518	250	402.34	1.507	.1780
105	168.98	1.142	.0575	255	410.38	1.517	.1809
110	177.03	1.157	.0632	260	418.43	1.527	.1837
115	185.08	1.171	.0687	265	426.48	1.537	.1865
120	193.12	1.186	.0740	270	434.52	1.546	.1892
125	201.17	1.200	.0793	275	442.57	1.556	.1919
130	209.22	1.215	.0844	280	450.62	1.565	.1944
135	217.26	1.229	.0894	285	458.66	1.574	.1969
140	225.31	1.243	.0943	290	466.71	1.583	.1994
145	233.36	1.256	.0991	295	474.76	1.592	.2018
150	241.40	1.270	.1038	300	482.81	1.600	.2042

$$C_W = 0.79 \div 0.0037\,W - 0.00000333\,W^2$$

Table 6. Relative humidity, coefficient of humidity, and log C_H.

H	C_H	Log C_H	H	C_H	Log C_H	H	C_H	Log C_H
%	----	----	%	----	----	%	----	----
0	1.202	.0799	36	1.026	.0110	61	.845	-.0732
4	1.187	.0745	37	1.019	.0083	62	.837	-.0774
6	1.179	.0717	38	1.013	.0055	63	.828	-.0818
8	1.171	.0687	39	1.006	.0028	64	.820	-.0862
10	1.163	.0655	40	1.000	.0000	65	.812	-.0907
12	1.154	.0623	41	.993	-.0030	66	.803	-.0953
14	1.145	.0588	42	.987	-.0059	67	.794	-.0999
16	1.136	.0553	43	.980	-.0089	68	.786	-.1047
18	1.126	.0516	44	.973	-.0119	69	.777	-.1096
20	1.116	.0477	45	.966	-.0150	70	.768	-.1145
21	1.111	.0457	46	.959	-.0182	71	.759	-.1196
22	1.106	.0437	47	.952	-.0214	72	.750	-.1247
23	1.101	.0417	48	.945	-.0247	73	.741	-.1300
24	1.095	.0395	49	.938	-.0280	74	.732	-.1354
25	1.090	.0374	50	.930	-.0314	75	.723	-.1409
26	1.084	.0352	51	.923	-.0349	76	.714	-.1465
27	1.079	.0330	52	.915	-.0384	78	.695	-.1581
28	1.073	.0307	53	.908	-.0420	80	.676	-.1702
29	1.068	.0284	54	.900	-.0456	82	.656	-.1829
30	1.062	.0260	55	.893	-.0493	84	.637	-.1961
31	1.056	.0236	56	.885	-.0531	86	.617	-.2100
32	1.050	.0212	57	.877	-.0570	88	.596	-.2245
33	1.044	.0187	58	.869	-.0609	92	.555	-.2559
34	1.038	.0162	59	.861	-.0649	96	.512	-.2907
35	1.032	.0136	60	.853	-.0690	100	.468	-.3298

$$C_H = 1.202 - 0.00353\,H - 0.0000381\,H^2$$

Table 7. Sunshine percentage, coefficient of sunshine, and log C_S.

S	C_S	Log C_S	S	C_S	Log C_S	S	C_S	Log C_S
%	----	----	%	----	----	%	----	----
0	.402	-.3958	51	.868	-.0614	76	.975	-.0110
4	.474	-.3245	52	.872	-.0595	77	.981	-.0083
7	.522	-.2825	53	.876	-.0577	78	.987	-.0056
10	.566	-.2474	54	.879	-.0559	79	.994	-.0027
13	.605	-.2179	55	.883	-.0541	80	1.000	.0002
16	.641	-.1929	56	.886	-.0523	81	1.007	.0032
18	.663	-.1783	57	.890	-.0506	82	1.015	.0063
20	.684	-.1652	58	.894	-.0488	83	1.022	.0095
22	.703	-.1533	59	.897	-.0470	84	1.030	.0128
24	.720	-.1425	60	.901	-.0451	85	1.038	.0162
26	.737	-.1327	61	.905	-.0433	86	1.046	.0197
28	.752	-.1239	62	.909	-.0415	87	1.055	.0233
30	.766	-.1158	63	.913	-.0397	88	1.064	.0270
32	.779	-.1084	64	.917	-.0377	89	1.074	.0308
34	.791	-.1017	65	.921	-.0358	90	1.083	.0347
36	.802	-.0956	66	.925	-.0338	91	1.093	.0388
38	.813	-.0899	67	.929	-.0318	92	1.104	.0429
40	.823	-.0847	68	.934	-.0297	93	1.115	.0472
42	.832	-.0799	69	.938	-.0276	94	1.126	.0515
44	.841	-.0753	70	.943	-.0254	95	1.138	.0558
46	.849	-.0711	71	.943	-.0232	96	1.150	.0540
47	.853	-.0691	72	.953	-.0209	97	1.162	.0652
48	.857	-.0671	73	.958	-.0185	98	1.175	.0700
49	.861	-.0651	74	.964	-.0161	99	1.188	.0749
50	.865	-.0632	75	.969	-.0136	100	1.202	.0799

$$C_S = 0.402 + 0.019\,S - 0.00028\,S^2 + 0.0000017\,S^3$$

Table 8. Elevation, coefficient of elevation, and log C_E.

Elev. E	Elev.	C_E	Log C_E	Elev. E	Elev.	C_E	Log C_E
1000 feet	meters			1000 feet	meters		
.0	0	.965	-.0153				
.1	30	.969	-.0137	3.6	1097	1.075	.0313
.2	61	.973	-.0121	3.7	1128	1.077	.0323
.3	91	.976	-.0106	3.8	1158	1.080	.0333
.4	122	.980	-.0089	3.9	1189	1.082	.0343
.5	152	.983	-.0074	4.0	1219	1.085	.0352
.6	183	.987	-.0059	4.1	1250	1.087	.0362
.7	213	.990	-.0044	4.2	1280	1.089	.0371
.8	244	.993	-.0029	4.3	1311	1.091	.0380
.9	274	.997	-.0014	4.4	1341	1.094	.0389
1.0	305	1.000	.0000	4.5	1372	1.096	.0397
1.1	335	1.003	.0014	4.6	1402	1.098	.0406
1.2	366	1.007	.0028	4.7	1433	1.100	.0414
1.3	396	1.010	.0042	4.8	1463	1.102	.0422
1.4	427	1.013	.0056	4.9	1494	1.104	.0431
1.5	457	1.016	.0069	5.0	1524	1.106	.0439
1.6	488	1.019	.0082	5.1	1554	1.108	.0446
1.7	518	1.022	.0095	5.2	1585	1.110	.0454
1.8	549	1.025	.0109	5.3	1615	1.112	.0462
1.9	579	1.028	.0121	5.4	1646	1.114	.0469
2.0	610	1.031	.0134	5.5	1676	1.116	.0476
2.1	640	1.034	.0146	5.6	1707	1.118	.0484
2.2	671	1.037	.0158	5.7	1737	1.120	.0491
2.3	701	1.040	.0171	5.8	1768	1.122	.0498
2.4	732	1.043	.0183	5.9	1798	1.123	.0505
2.5	762	1.046	.0194	6.0	1829	1.125	.0511
2.6	792	1.049	.0206	6.1	1859	1.127	.0518
2.7	823	1.051	.0218	6.2	1890	1.128	.0524
2.8	853	1.054	.0229	6.3	1920	1.130	.0530
2.9	884	1.057	.0240	6.4	1951	1.132	.0536
3.0	914	1.060	.0251	6.5	1981	1.133	.0542
3.1	945	1.062	.0262	6.6	2012	1.135	.0548
3.2	975	1.065	.0272	6.7	2042	1.136	.0554
3.3	1006	1.067	.0283	6.8	2073	1.138	.0559
3.4	1036	1.070	.0293	6.9	2103	1.139	.0565
3.5	1067	1.073	.0304	7.0	2134	1.140	.0570

$$C_E = 0.9654 + 0.0362\,E - 0.0016\,E^2$$

Table 9. Regional groups for which mean monthly values of C_M are given in Table 10.

Group	Latitude Range	Location
	South	
1	12	Instituto Geofisico del Peru, Huancayo, Peru (Elev. 10,870 feet)
	North	
2	4 - 13	Nigeria and Panama
3	18 - 22	Puerto Rico and Hawaii
4	26 - 34	East Texas and Georgia
5	31 - 34	West Texas and Arizona
6	33	Chula Vista, California
7	34 - 37	Backus Ranch and Friant G. C., California
8	38 - 40	North-Central California
9	38 - 42	Iowa and Indiana
10	38 - 39	Milford, Utah, and Grand Junction, Colorado
11	38 - 41	Pueblo and Estes Park, Colorado
12	40 - 42	Northern Utah
13	42 - 45	Western Oregon
14	45 - 49	Western Montana
15	46 - 48	Prosser and Seattle, Washington
16	43 - 62	Moses Lake, Washington, Canada and Alaska

Table 10. Monthly coefficients by groups.

Group	Latitude Range	Months of Record	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
	South													
1	12	34	1.24	1.23	1.25	1.24	1.21	1.22	1.33	1.34	1.26	1.20	1.16	1.17
	North													
2	4 - 13	127	0.93	0.96	0.96	1.00	0.93	0.94	0.90	0.90	0.92	0.93	0.96	0.95
3	18 - 22	140	1.10	1.08	1.05	1.05	1.04	1.025	1.04	1.03	1.05	1.06	1.065	1.10
4	26 - 34	688	1.10	1.05	1.00	0.94	0.90	0.94	0.95	0.98	1.00	1.05	1.14	1.19
5	31 - 34	638	0.95	1.00	1.02	1.02	0.99	0.98	1.00	0.98	0.98	1.00	1.00	1.00
6	33	120	0.96	1.00	1.02	1.05	1.05	1.07	1.05	1.07	1.05	1.10	1.10	1.05
7	34 - 37	205	1.04	1.05	1.05	1.08	1.09	1.09	1.12	1.18	1.23	1.25	1.27	1.18
8	38 - 40	421	0.88	0.85	0.95	1.00	1.00	1.00	0.99	1.03	1.04	1.03	0.97	0.89
9	38 - 42	99	----	----	----	0.92	0.90	0.90	0.90	0.95	0.98	1.05	----	----
10	38 - 39	115	----	----	----	1.20	1.15	1.08	1.10	1.10	1.13	1.20	1.33	----
11	38 - 41	125	----	1.15	1.10	0.90	0.88	0.85	0.84	0.83	0.87	1.04	1.04	----
12	40 - 42	325	----	----	0.85	0.85	0.84	0.84	0.83	0.88	0.92	0.94	----	----
13	42 - 45	213	0.75	0.77	0.85	0.93	0.94	0.97	1.00	1.03	0.95	0.90	0.80	0.70
14	45 - 49	168	----	----	----	0.97	0.90	0.88	0.90	1.00	1.00	0.98	----	----
15	46 - 48	130	----	0.65	0.75	0.75	0.80	0.80	0.85	0.87	0.85	0.80	0.75	----
16	43 - 62	100	----	----	----	1.18	1.13	1.08	1.05	1.05	1.10	1.15	----	----